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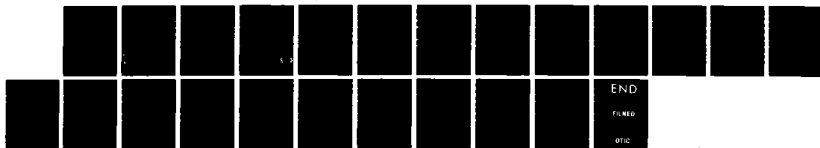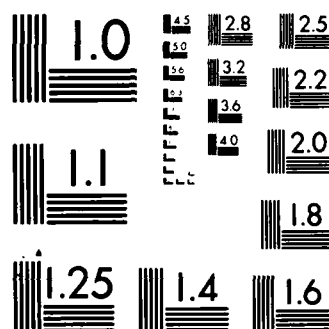   TOPOGRAPIIC CENTER WASHINGTON DC   G T VILLADSEN ET AL.
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At the Defense Mapping Agency's Hydrographic/Topographic Center (DMAHTC), the only manual stereoplotter currently in use is the Analytical Stereoplotter II (AS-11).

Because of its elevation sampling algorithms, digital elevation data sets produced on the AS-11 are not digital elevation matrices (DEM's).

However, all of DMAHTC's orthophotoprinters require object space elevation data in DEM format.

In order to enable DMAHTC to produce orthophotographs from elevation data collected on the AS-11, FORTRAN software was developed on DMAHTC's mainframe UNIVAC computer for transforming AS-11 elevation data into orthophotoprinter-compatible DEM's.

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~This paper describes the techniques employed for resampling and for filling large empty areas within the DEM such as those caused by cloud cover and large water bodies. Originator Supplied Keywords-

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ABSTRACT

Because of its elevation sampling algorithms, digital
elevation data sets produced on the Analytical Stereoplotter
II (AS-11) are not digital elevation matrices (DEM's).
However, orthophotoprinters require object space elevation
data in DEM format. In order to produce orthophotographs
from elevation data collected on the AS-11, FORTRAN software
was developed on a Sperry computer for transforming AS-11
elevation data into orthophotoprinter-compatible DEM's. This
paper describes the techniques employed for resampling and
for filling large empty areas within the DEM such as those
caused by cloud cover and large water bodies.

INTRODUCTION

An orthophotograph is an aerial photograph which has been artificially deformed in such a manner that the orthophotograph space-to-object space coordinate transformation is a two-dimensional conformal transformation which is independent of object space elevation. All orthophotoprinters use non-simultaneous exposure of the orthophotograph to deform the aerial photograph. At any time, only a small window of exposure is open. It is convenient to have this window of exposure sweep through object space and orthophotograph space in a uniform pattern while accomplishing deformation in the image space of the aerial photograph. For this reason, most off-line orthophotoprinters require uniformly distributed object space elevations in the form of a digital elevation matrix (DEM). However, it can be difficult and is not always desirable to collect a DEM on a manual stereoplotter such as the AS-11. Therefore, it is necessary to develop a method to convert non-regularly spaced, scanned stereoplotter data into a regular, rectangular DEM. We first consider the manual data collection methods and orthophotoprinter requirements peculiar to the AS-11 and the available orthophotoprinters and then describe a method to resample stereoplotter observations to form a DEM. Furthermore,

software algorithms for filling missing data areas are discussed.

THE AS-11 MANUAL STEREOPLOTTER

It was required to produce orthophotographs from elevation data collected on two versions of the same basic manual stereoplotter: the AS-11-AM and the AS-11-P. Both are optical train systems manufactured by the Ottico Meccanica Italiana Corporation of America.

The simplest and most accurate method of collecting a DEM on a manual stereoplotter would be to drive to a point, wait for the operator to remove stereoscopic parallax, sample the elevation when he confirms that he has removed parallax, store the elevation, drive to the next point, and repeat the procedure. This method would also be by far the slowest. Analytic stereoplotters can assist the operator in order to accelerate the data collection process. The stereoplotter can scan the model automatically while the operator keeps the measuring mark on the terrain. The type of digital model obtained will be determined by the elevation sampling scheme used while scanning.

The AS-11 Sampling Algorithm

The AS-11-AM sampling algorithm does not collect a true DEM. The AS-11-AM uses only a near-constant sampling interval. Before profiling, the AS-11-AM operator specifies

a nominal point spacing. During collection, the AS-11-AM
samples the current object space coordinates of the
reference mark every twenty milliseconds. If the distance
from the last point is less than the sampling interval, the
AS-11-AM will wait for another twenty milliseconds and
resample. If the distance is greater than or equal to the
sampling interval, the AS-11-AM will sample and store the
current object space coordinates of the reference mark. In
effect, the operator supplies a minimum sampling interval,
but the maximum point spacing is dependent on scanning
speed.

In contrast, the AS-11-P does have a constant sampling
interval in model space and does produce regularly spaced
elevation profiles.

Void Areas Within the Digital Compilation

Data compatibility with an orthophotoprinter may also
require the DEM to be rectangular. There are two reasons
AS-11-AM and AS-11-P elevation data sets are not usually
rectangular in model space: 1) gaps and 2) model
segmentation.

Intentional Gaps

The first cause of void regions is that the operators are
allowed to adjust the nominal DEM object space limits at any
time. Collecting a densely spaced elevation data set from a
stereomodel can be a very time-consuming process. If part of

the stereomodel is not required for the current project, or
if part of the stereomodel is obscured by clouds, covered by
snow, or occupied by a large body of water, it is desirable
to avoid collecting that part.

Segmentation

The second cause of void regions is model segmentation. A
segment is that portion of a stereomodel collected between
one interior and exterior orientation and the next.Usually,
the segments do not add up to a full rectangular DEM.

Summary

To summarize, transformation of an AS-11-AM elevation data
set into a DEM requires both resampling and void fill, while
transformation of an AS-11-P elevation data set into a DEM
requires only void fill.

CHARACTERISTICS OF THE RPIE AND OLOPS ORTHOPHOTOPRINTERS

It was required to produce orthophotographs on two different orthophotoprinters: the RPIE (Replacement of Photographic Equipment) and the OLOPS (Off-Line Orthophoto Printing System). The RPIE is an optical train, off-line orthophotoprinter designed and built by Bendix, Incorporated. The OLOPS is a video image transfer off-line orthophotoprinter designed and built by Baker and Associates.

Differential Exposure Strategies

Orthophotoprinters can be divided into two major classes according to the shapes of their differential exposure windows: 1) line-element strip orthophotoprinters and 2) plane-area element orthophotoprinters. In plane-area element orthophotoprinters, small areas which are rectangular in object and orthophotograph space but quadrilateral in image space are exposed discretely, one at a time. In line-element strip orthophotoprinters, a line which has constant length and constant angular orientation in object space and orthophotograph space (but not image space) is continuously exposed. The line is effectively considered to have no width. Both the RPIE and the OLOPS are line-element strip orthophotoprinters.

Void Areas

For the purpose of orthophotograph production from elevation data collected on an AS-11, the most significant

difference between the RPIE and the OLOPS lies in how each

system responds to void areas in the DEM.

Void Fill for the OLOPS

Each point in the OLOPS DEM file has a corresponding

figure-of-merit variable associated with it.   The

figure-of-merit may be assigned a value to indicate that the

current point is invalid.   If any of the four nearest

neighbors to either end of the line of exposure have invalid

figures-of-merit, the OLOPS will turn off its light source

until the line reaches an area in the DEM where all eight of

those figures-of-merit are valid again.

Void Fill for the RPIE

There are no figures-of-merit in a RPIE DEM.   Reasonable

estimates of elevation for all void areas in the DEM must be

supplied.   The estimates must be good because steep slope

anomalies can cause the printer scan shaping mechanisms to

run into their mechanical limits.

GENERATION OF A DEM

FROM AS-11 ELEVATION DATA

Two FORTRAN programs were written on a Sperry mainframe computer to perform DEM generation. The PASS-RPIE program produces a RPIE-compatible DEM and the PASS-OLOPS program produces an OLOPS-compatible DEM. PASS is an acronym for Pooled Analytical Stereoplotter Systems. PASS-RPIE is the more versatile of the two programs. It will transform either AS-11-AM or AS-11-P elevation data while PASS-OLOPS will transform only the more highly ordered AS-11-P elevation data.

PASS-OLOPS Algorithm

Since all AS-11-P data has constant sampling intervals, PASS-OLOPS uses them as the OLOPS DEM sampling intervals. First, PASS-OLOPS reads an AS-11-P profile into computer memory. Then it locates and reads in the orthophotograph DEM profile with the same object space x coordinate, computes the starting address within the orthophotograph profile of the first point in the AS-11-P profile, and transfers the AS-11-P profile into the orthophotograph profile as a block. In effect, PASS-OLOPS only resamples the first point in each AS-11-P profile. Because the OLOPS does not expose the orthonegative when its window of differential rectification contains invalid elevations as indicated by the figure-of-merit, PASS-OLOPS does not need to fill void gaps in the OLOPS DEM.

PASS-RPIE Algorithm

Resampling Interval

PASS-RPIE uses the nominal AS-11 sampling intervals as the
RPIE DEM sampling intervals. This technique insures that
all points in the input data set are at or within one-half
sampling interval of an orthophotograph DEM matrix point.
The nominal intervals are extracted from the AS-11 elevation
data rather than input by the program user. For each
profile in the data set, a nominal point spacing is
calculated by averaging five intervals within the first
fifty points. The final point spacing is calculated by
averaging the nominal point spacings of all profiles in the
data set.

The interval between consecutive profile pairs is also
computed and saved. The mean profile spacing interval and
the standard deviation of the sample are computed. All
intervals outside the range of the mean plus or minus one
standard deviation are deleted. The mean profile spacing is
then recomputed and used as the final profile spacing. This
procedure is necessary because the AS-11-AM operator may
interrupt profiling at any time and restart at any location
within the stereomodel. Since the elevation data are stored
in the same order as they are collected, any particular
consecutive profile pair may not be necessarily separated by
a correct profile spacing. In practice, many AS-11-AM
elevation data sets have enough large profiling interrupts

to bias a profile spacing simply averaged over the whole data set unless extrema are deleted.

Resampling Algorithm

Because the AS-11-AM does not have a constant point increment, PASS-RPIE does not transfer observed profile elevations as a consecutive block. Instead, it resamples every elevation in the AS-11 elevation data set to its nearest neighbor in the RPIE DEM. If more than one elevation in the AS-11 data set falls on the same DEM post (overlap), the latest elevation takes precedence. The "latest nearest neighbor" resampling algorithm is consistent with the two reasons for overlap in an AS-11-AM elevation data set: segmentation and retracing. Experience has shown that where segments overlap, the differences in elevation at common points do not produce a significant error in orthophotograph image space. In manual profiling mode on the AS-11-AM, the operator has the option to recollect part of the current profile. This retracing is used to correct blunders. With this procedure, both the original bad elevations and the recollected elevations are stored in the original data set. However, since elevations are always stored in the same order as they are collected, the latest nearest neighbors will be adopted thereby replacing the previous incorrect data.

Accuracy Assessment of the Resampling Algorithm

To assess the accuracy of the latest nearest neighbor

resampling algorithm, we seek to determine the horizontal

object space displacement corresponding to a given error in

DEM grid point elevation. Assuming near vertical

photography, the relief displacement equation yields a

relationship between image displacement and vertical terrain

displacement.

$$Dr = r \times DZ/(ZL-Z) \qquad (1)$$

where

Dr = image displacement ,

DZ = vertical change in terrain elevation ,

r = radial distance from principal point ,

$(ZL-Z)$ = flying height above terrain.

Now let D equal the horizontal distance between the nearest

neighbor observed elevation and the DEM grid location

assigned to that elevation, and let v equal the terrain

slope at the nearest neighbor point. The vertical terrain

displacement at the grid point is then

$$DZ = D(\tan v) \qquad (2)$$

Furthermore, if we scale the image displacement to a

corresponding horizontal object space displacement, DR, by

$$DR = Dr \times (ZL-Z)/f \qquad (3)$$

and substitute Equations 2 and 3 into Equation 1, we obtain

$$DR = D(\tan v) \times r/f \qquad\qquad (4)$$

where f is the camera focal length. Clearly, the horizontal error is minimized by using small scale photography, but for a given flight plan, the sampling interval will control D and terrain roughness will determine v. The smaller the sampling interval, the smaller D is likely to be, and consequently the smaller the orthophotograph image placement error DR. However, smaller sampling intervals also increase the probability of large local terrain slope angles. A reasonable estimate for the maximum local terrain slope angle is thirty degrees, which is approximately the maximum angle at which soils and talus form stable hillsides.

Table 1 evaluates Equation 4 for near-vertical 9-inch format photography and

$$f = \text{focal length} \qquad = 152.4 \text{ mm}$$
$$r = \text{maximum radial distance} = (114^2 + 114^2)^{1/2}$$
$$= 162 \text{ mm}$$

It is apparent that the latest nearest neighbor algorithm can induce unacceptable orthophotograph image placement errors unless the input elevation data was collected on an AS-11-P (in which case D always equals zero) or the AS-11-AM operator specifies a suitably dense sampling interval.

Table 1. Object Space Displacements Caused by
Nearest Neighbor Resampling

D (meters)

----

v		10	20	50	75	100	150	200
(degrees)								

5		0.9	1.8	4.6	6.9	9.2	13.8	18.4
10		1.9	3.7	9.3	13.9	18.5	27.8	37.1
20		3.8	7.7	19.1	28.7	38.3	57.4	76.6
30		6.1	12.1	30.4	45.6	60.7	91.1	121.5
40		8.8	17.7	44.1	66.2	88.3	132.4	176.5

Horizontal Displacements (meters)

ESTIMATING ELEVATIONS FOR VOID AREAS IN THE DEM

There are two kinds of void gaps in the RPIE DEM: 1) point
gaps and 2) segment gaps. Point gaps are small gaps embedded
in a RPIE profile occurring where consecutive AS-11-AM
profile points are not nearest neighbors to consecutive RPIE
profile points. This usually occurs in low-relief areas of
the stereomodel where the AS-11-AM operator maximizes
profiling speed. Missing segments may occur in either
AS-11-AM or AS-11-P elevation data. PASS-RPIE must fill
them with reasonable estimates of elevation. The objective
is not to produce usable orthophotograph imagery in segment
gap areas, but to prevent slope anomalies along segment gap
boundaries from causing the RPIE to exceed its hardware
limitations. Thus the critical factor in PASS-RPIE segment
gap fill is the prevention of slope anomalies around segment
gap boundaries.

Elevation Estimation

PASS-RPIE handles gap fill by making three passes through
the RPIE DEM. The first pass makes elevation estimates for
all void points in the matrix. The second and third passes
constrain all slopes between neighboring points to a maximum
absolute value.

The procedure used in the first pass is as follows:

a. Read a profile into memory.

b. Locate the first valid elevation in the profile.
    Extend it back to start-of-profile.

c. Locate the last valid elevation in the profile.
    Extend it out to end-of-profile.

d. If there are no valid elevations in the profile,
    copy the previous profile.

e. Linearly interpolate across void gaps of any size
    embedded in the RPIE profile.

f. Write the filled profile back to disk.

PASS-RPIE repeats these steps for all profiles in the DEM.

After the first pass, you will have a DEM without void
points. Unfortunately, you will also often have
unacceptable slope anomalies along segment gap boundaries.

Slope Anomaly Elimination

During the execution of this step, PASS-RPIE has a two
profile window open on the DEM. The profiles are always a
consecutive pair.

On the first pass:

$$XSLAVE = XMASTER + DX$$

On the second pass:

$$XSLAVE = XMASTER - DX$$

Where

XMASTER = object space x coordinate of master profile

XSLAVE = object space x coordinate of slave profile

DX   = object space x coordinate spacing of

RPIE DEM

PASS-RPIE carries figures-of-merit similar to those used by the OLOPS (but it does not write them out to the final RPIE file). When PASS-RPIE encounters a slope anomaly, it checks the figures-of-merit of the offending points. If they are both valid or both invalid, the slave point elevation is changed to conform to the master point elevation. If one figure-of-merit is valid and one is invalid, the slave point is changed only if it has the invalid figure-of-merit. Thus valid elevations are never changed to fit to invalid elevations.

A slope anomaly occurs when the absolute value of the slope between neighboring points exceeds a maximum. If the slope angle is less than the maximum negative slope angle, the slope angle is forced to equal the maximum negative slope angle. If the slope angle is greater than the maximum positive slope angle, the slope angle is forced to equal the maximum positive slope angle. The current maximum slope angle is approximately thirty degrees. The selection of this threshold value was empirical rather than theoretical; it is sufficient to prevent the RPIE from exceeding its

hardware limits while it does not smooth out valid terrain detail.

After the slopes have been checked across the profiles, they are checked along the slave profile (in the object space y direction) the slave profile becomes the new master profile, a new slave profile is read into computer memory, and the process is reinitiated. PASS-RPIE performs this procedure for all profiles in the RPIE DEM.

Figures 1 and 2 illustrate slope anomaly correction around a segment gap by the PASS-RPIE program.

CONCLUSIONS

Dense sampling of a non-matrix elevation data set is essential to accuracy if the data set is to be resampled into an orthophoto-compatible DEM.

Effective techniques for handling large void areas within the non-matrix data set may be implemented within the software domain.

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